DEVELOPMENT OF A COMPACT MARX GENERATOR FOR HIGH-POWER MICROWAVE APPLICATIONS

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Abstract

One of the goals of the High-Energy Sources Division of the Advanced Weapons and Survivability Directorate at the Phillips Laboratory is to develop high-power microwave sources and the related pulsed power. The development of a compact Marx generator to drive loads with impedances on the order of 10 Ohms will be discussed. It is an 8 stage design, 4 stages charged to +100kV and 4 stages charged to -100kV, that stores 19.2 kJ at full charge. The Marx, excluding the trigger generator, has a diameter of 0.9 m and a height of 0.7 m. The entire assembly is housed in a 1.2 m diameter aluminum pipe pressurized with 30 psig sulfur-hexafluoride. The same sulfur-hexaflouride that insulates the Marx from its container also serves as the working gas in the gas-insulated switches of the Marx. In experiments to date the Marx has been fired hundreds of times at full voltage into loads varying in impedance from 5 to 10 Ohms. The design and fabrication of the Marx generator and the experimental results will be given.

Introduction

Members of the Narrow-band Source Branch have undertaken the development of a new pulsed power driver to be used in the testing of novel high-power microwave (HPM) sources. Some of the desired characteristics of this source will be given. It must be compact, lightweight, rugged, and reliable so that it may be used outdoors for testing in the future and also to investigate the transition of pulsed power from the laboratory to an operational environment. The primary source under investigation by this group is the MILO, so the pulser was designed to drive this device. For this application the pulser should be capable of driving a load impedance of 5 to 10 Ohms at up to 500 kV for pulse lengths of a few hundred nanoseconds. A Marx generator that satisfies most of the listed requirements has been fabricated and tested. Operation into a 7 Ω water resistor at approximately 500 kV for a full-width, half-maximum pulse width of 500 ns has been demonstrated. The system is more compact and lightweight than other systems of comparable performance. The ruggedness and reliability of the system have not been

0-7803-4214-3/97/$10.00 © 1997 IEEE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1997	**N/A**	**-**

4. TITLE AND SUBTITLE
Development Of A Compact Marx Generator For High-Power Microwave Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
PLAVSQN Kirtland AFB, NM 87117

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
One of the goals of the High-Energy Sources Division of the Advanced Weapons and Survivability Directorate at the Phillips Laboratory is to develop high-power microwave sources and the related pulsed power. The development of a compact Marx generator to drive loads with impedances on the order of 10 Ohms will be discussed. It is an 8 stage design, 4 stages chargedto+100kV and 4 stages charged to - 100kV, that stores 19.2 kJ at full charge. The Marx, excluding the trigger generator, has a diameter of 0.9 m and a height of 0.7 m. The entire assembly is housed in a 1.2 m diameter aluminum pipe pressurized with 30 psig sulfur-hexafluoride. The same sulfur-hexaflouride that insulates the Marx from its container also serves as the working gas in the gas-insulated switches of the Marx. In experiments to date the Marx has been fired hundreds of times at full voltage into loads varying in impedance from 5 to 10 Ohms. The design and fabrication of the Marx generator and the experimental results will be given.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**6**	

investigated at this time but it is believed that the system can be made both rugged enough and reliable enough for field use. The design and development of the pulser will be discussed and some waveforms depicting the system performance will be shown. Another Marx generator of similar design but oriented toward laboratory use is also being developed at the Phillips Laboratory[1].

System Description

A photograph of the assembled Marx generator ready to be placed in the pressure vessel is shown in Figure 1. The Marx consists of 8 stages, four charged to a maximum voltage of +100 kV and four charged to a maximum voltage of -100 kV to give a maximum output voltage into an open circuit of 800 kV. The entire assembly is enclosed in an aluminum pressure vessel that is filled with SF_6 to a pressure of 32 psig for operation at the maximum charge voltage of ±100 kV. For operation at lower voltages the pressure in the vessel is reduced. The SF_6 that insulates the Marx from the containment vessel also serves as the working gas in the main Marx switches. The high voltage end of the Marx (the bottom in Fig. 1) is connected through an insulator stack to the load and is attached mechanically to the pressure vessel with the G-10 plate shown at the very bottom of the figure. The ground end of the Marx (the top in Fig. 1) is attached electrically and mechanically to the pressure vessel with an aluminum plate.

One of the bi-polar stages is shown in Fig. 2. Each of the ±100 kV stages consists of six 0.08 μF capacitors connected in parallel. Single-ended plastic case capacitors manufactured by Maxwell Laboratories, Inc. are used. There are three of the assemblies shown in Fig. 2 stacked up to form the middle of the Marx and an unipolar half-stage is on each end. The operational and physical characteristics of the Marx generator are listed in Table 1.

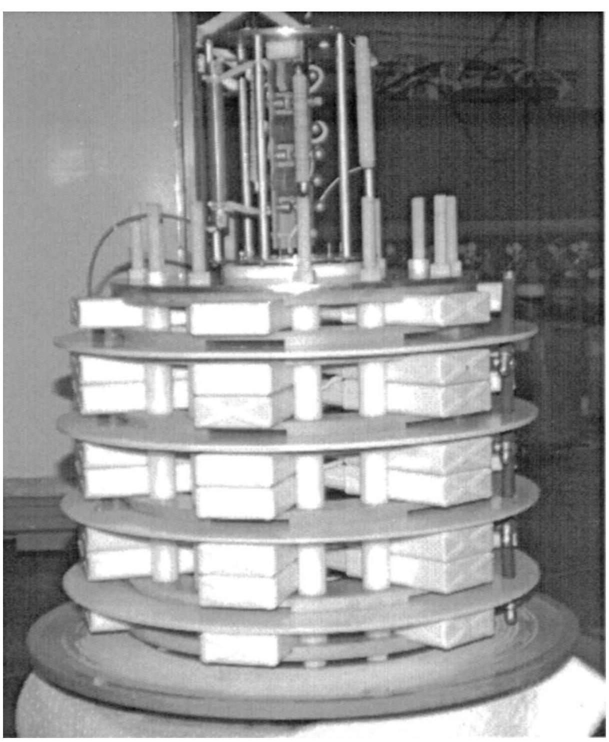

Figure 1. Assembled Marx Generator Ready to go into the Pressure Vessel.

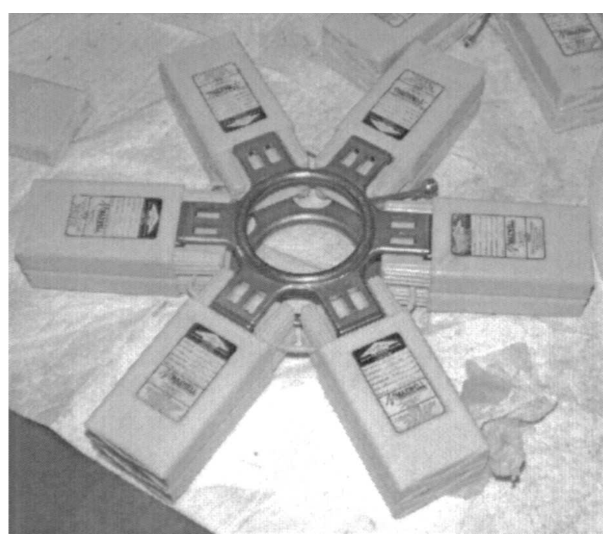

Figure 2. Assembled Bi-Polar Stage Showing the Switch Electrode.

Table 1. Characteristics of the Marx Generator

Erected Capacitance:	60 nF
Open-Circuit Voltage:	150 - 800 kV
Maximum Charge Voltage:	±100 kV
Stored Energy at Full Charge:	19.2 kJ
Marx Inductance:	< 400 nH
Diameter of the Marx:	1.2 m
Height of the Marx without Trigger Generator:	0.7 m
Mass of the Marx Alone:	405 kg
Mass of the Marx and Pressure Vessel:	864 kg

More details of the Marx hardware will now be given using Fig. 3 for reference. Six capacitors are arrayed around the switch electrode which is a rail gap fabricated from brass. An G-10 annulus with slots cut in it for the capacitor cases to fit in is then fitted to the array of capacitors. This assembly is depicted in the left side of Fig. 3. These stages are then stacked on the G-10 plate that makes the mechanical connection to the pressure vessel on the high voltage end. Twelve 2.54 cm diameter G-10 rods pass through the holes in the annuli and are threaded into the G-10 plate on the high-voltage end. The stack is held together by threading nuts on the G-10 rods at the low-voltage end of the Marx. The trigger generator is attached to the ground plate on the low-voltage end of the Marx and then the entire assembly is mounted in the pressure vessel. Bi-polar charging of the Marx is accomplished through two strings of 100 Ω carbon power resistors.

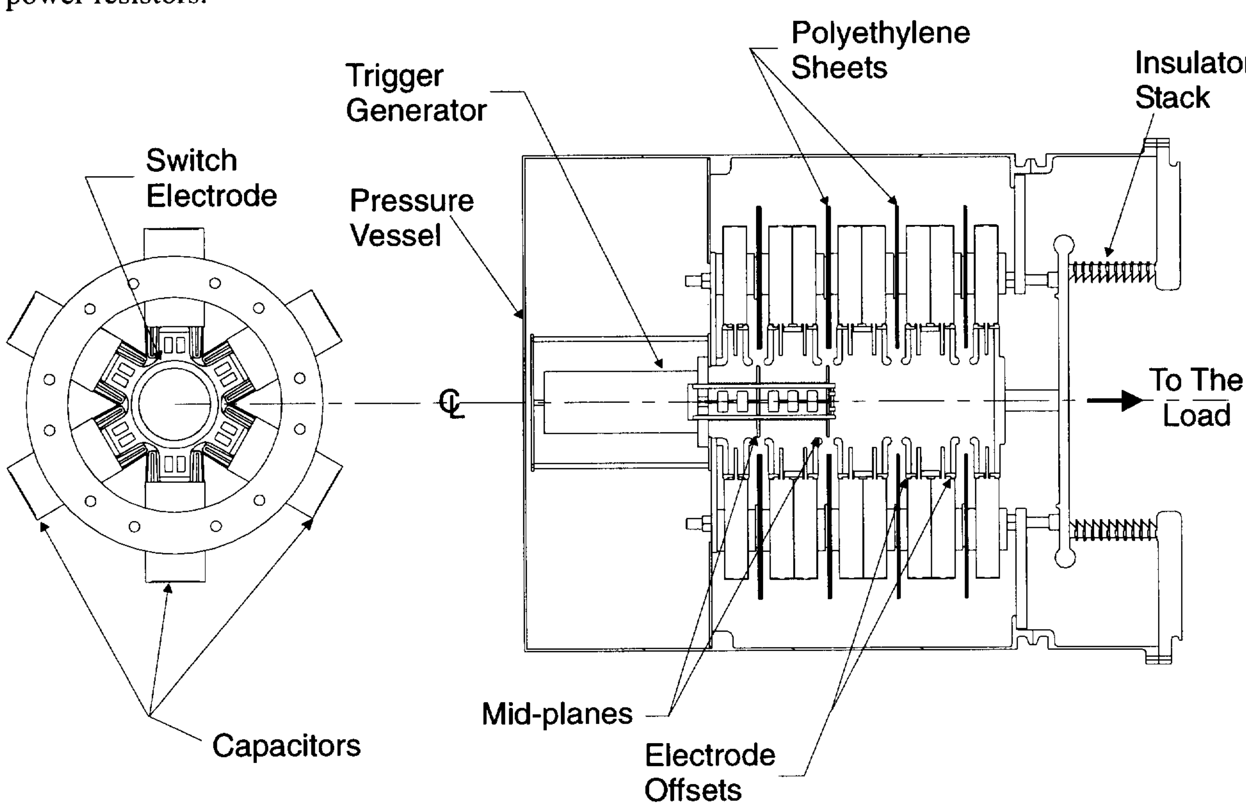

Figure 3. Diagram Showing the End and Side Views of the Marx Generator.

The 0.32 cm thick polyethylene sheets shown in Fig. 3 serve two purposes. First, the gap spacing in the switches is determined by how many sheets are included per stage. Second, the sheets stop surface tracking along the capacitor cases from stage to stage within the Marx. The electrode offsets also stop arcing within the Marx generator. In the original design the switch electrodes were bolted directly to the capacitor electrodes. During initial tests it was found that at higher charge voltages (V > ±90 kV) an arc would form from the switch electrode across the capacitor header to the ground electrode of the capacitor. Offsetting the switch electrode 1.27 cm away from the header prevented this. At first the Marx was constructed without the polyethylene sheets or the electrode offsets. It was found, through a series of tests charging the Marx to successively higher voltages, that they were required for operation at the full charge voltage of ±100 kV.

The trigger for the Marx is provided by a small three stage Marx generator made up of ceramic capacitors. It is charged off of one of the high-voltage lines used to charge the main Marx generator. The trigger Marx is triggered by a commercial 50 kV trigger generator. The output of the trigger Marx is coupled through an LC tank circuit to the mid-plane field distortion electrodes located in the first two switch gaps of the main Marx generator. The LC tank circuits consist of an inductor wound around (in parallel with) ceramic capacitors in series. The inductor allows the biasing of the trigger planes at ground, the ceramic capacitors in parallel pass the high frequency output of the trigger Marx to the trigger planes, and the parallel impedance of the tank circuit is high compared to the load so that the energy of the main Marx is delivered to the load and not the trigger Marx.

The inductance of the Marx was obtained during its initial testing. That is, there was an arc from the metal plate on top of the insulator stack out to the pressure vessel wall. This should provide a pretty good measure of the inductance of the Marx alone. The current waveform for this shot, taken from a passively integrated Rogowski coil, is shown in Fig. 4. The amplitude of the signal at the beginning of the pulse was clipped by the digitizer. For a period, T, of 950 ns and an erected capacitance, C, of 60 nF, then using:

$$L = \frac{T^2}{(2\pi)^2 C} \tag{1}$$

one obtains a value for the Marx inductance of 381 nF.

Marx Generator Operation

After the initial verification that the design was viable the Marx has been tested into two basic load configurations. The first was a fairly low inductance resistive load that simulates direct driving an HPM device such as a magnetically insulated line oscillator (MILO)[2]. The second was a capacitor bank that simulates a water pulse forming line (PFL). In the second case the PFL would be used to drive an HPM device with a more rectangular pulse than could be obtained directly from the Marx generator. More details of these test configurations will now be given.

The resistive load used in the first series of shots consisted of a water resistor located in the region labeled "To the Load" in Fig. 3. It was of coaxial design and resulted in a fairly low total system inductance of less than 500 nH. The voltage was monitored with a resistive divider that went from the metal plate on top of the insulator stack out to the pressure vessel wall and the

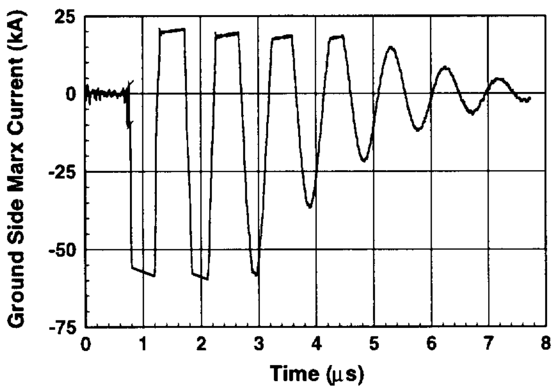

Figure 4. Current Waveform used to Calculate the Marx Generator Inductance.

current was monitored with both a Rogowski coil and a current viewing resistor (CVR) in series with the load. All of the signals were recorded on transient digitizers. Figures 5 and 6 show the Marx voltage and load current for a shot with the following parameters: charge voltage, $V_{ch} = \pm 90$ kV, operating pressure, $P_M = 25$ psig, and load resistance, $R_L \approx 7\ \Omega$. The risetime of the current in this configuration was approximately 150 ns.

The second test configuration was intended to simulate a PFL for the case where a fast risetime, flat-top pulse was required by the load. An available 28 nF capacitor bank rated at 1.2 MV was used to simulated the water line and a 5 μH inductor was located between the Marx and the load capacitance. The waveforms from a shot in this test are shown in Figs. 7-9. The Marx voltage was monitored as described previously, the Marx current was monitored with a Rogowski coil, and the capacitive load voltage probe was a resistive divider. The operating parameters for the displayed shot were: charge voltage, $V_{ch} = \pm 95$ kV, operating pressure, $P_M =$ 30 psig The results of this test verify that the Marx generator can be used to charge a pulse line as well as to direct drive an HPM load.

Over 1000 shots, 100's of those at full rated voltage, were conducted in the above listed configurations. The Marx has proven to be fairly reliable and operates very consistently for this level of development. It was learned, the hard way, that it only takes one low inductance short at full charge voltage, similar to that illustrated in Fig. 4, to catastrophically fail several of the capacitors within the Marx. When the Marx generator is consistently operated at full voltage another problem arises. After approximately 100 shots one of the capacitors in the half-stage on the ground end fails. The cause of this failure is unknown at this time but circuit simulations show that high-voltage transients can be induced in this stage by the inductance of the ground plate and the stray capacitance to this plate. This will be investigated in the future.

During the development of this system it has been discovered that the Marx generator can usually be repaired easily and quickly. A two person team can disassemble, repair, reassemble, and ready the system for operation in less than one day. If the Marx must be repaired often then a considerable quantity of SF_6 can be consumed, which can get costly, hence the parallel

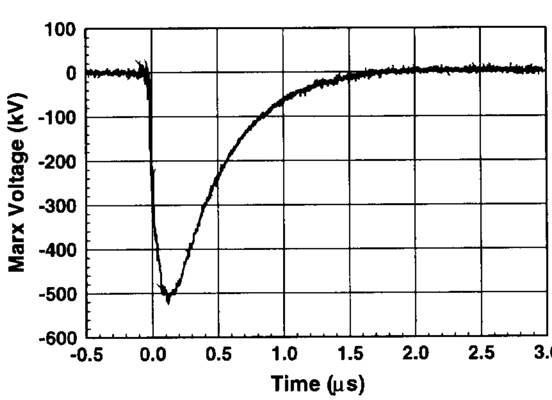

Figure 5. Marx Voltage Across a 7 Ω Resistive Load.

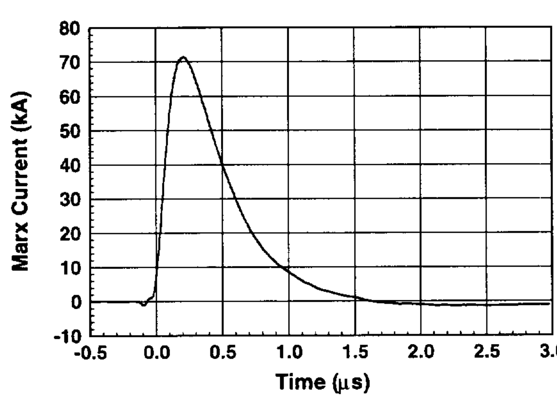

Figure 6. Marx Current Through a 7 Ω Resistive Load.

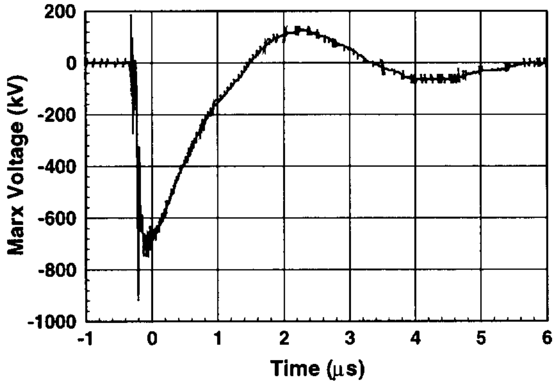

Figure 7. Marx Voltage when Charging a Pulse Forming Line.

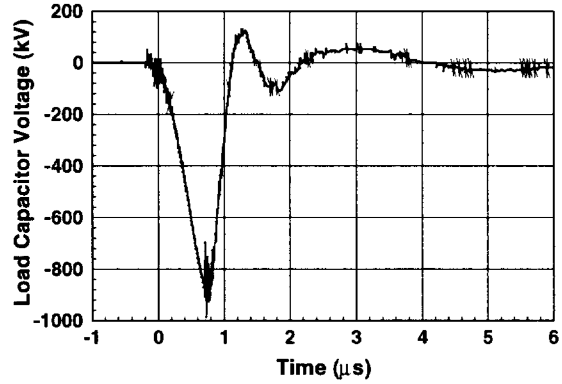

Figure 8. Load Voltage when Charged by the Compact Marx Generator.

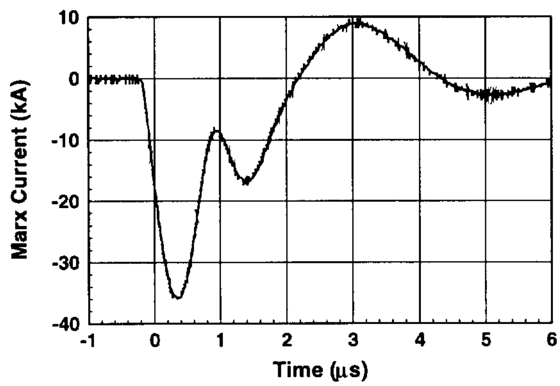

Figure 9. Current Through the Marx During Charging of the PFL Simulator.

development effort cited in reference 1. For a fieldable system the flexibility provided by using the SF_6 as the insulating medium and the lighter overall system weight justify the cost of the SF_6. The focus of future work will be to mitigate the loss of the ground stage capacitors every 100 shots or so, improve reliability and ruggedness of the system, and finally to investigate rep-rate operation.

Summary

A compact, lightweight, rugged Marx generator has been designed, fabricated, and tested. It has proven suitable for direct driving low impedance (~ 5 Ω) loads or charging pulse forming lines. The system has been fired over 1000 times in both horizontal and vertical orientations.

Acknowledgments

The authors would like to thank Mr. David Trujillo, Mr. Daniel Martinez, and Mr. Peter Ingwersen for their dedication and hard work.

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[1] J.D. Graham, et al. "Compact 400kV Marx Generator with Common Switch Housing," 11th IEEE International Pulsed Power Conference, Baltimore, MD, June 29 - July 2, 1997.
[2] R.W. Lemke, S.E. Calico, and M.C. Clark, "Investigation of a Load-Limited, Magnetically Insulated Transmission Line Oscillator (MILO)," *IEEE Trans. Plasma Sci.*, vol. 25, p. 364, 1997.